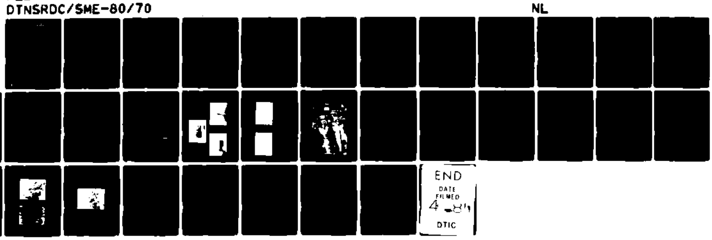
AD-A096 049 DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CE--ETC F/G 13/8
INFRARED TEMPERATURE SENSING OF COOLING RATES FOR ARC WELDING C--ETC(U)
FEB 81 W E LUKENS, R A MORRIS, E C DUNN

UNCLASSIFIED DTNSRDC/SME-80/70 NL

1 OF 1
AD
A096049



LEVEL II

(12)

DTNSRDC/SME-80/70

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

AD A096049

INFRARED TEMPERATURE SENSING OF COOLING RATES FOR ARC WELDING CONTROL

by

W. E. Lukens
R. A. Morris
E. C. Dunn

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

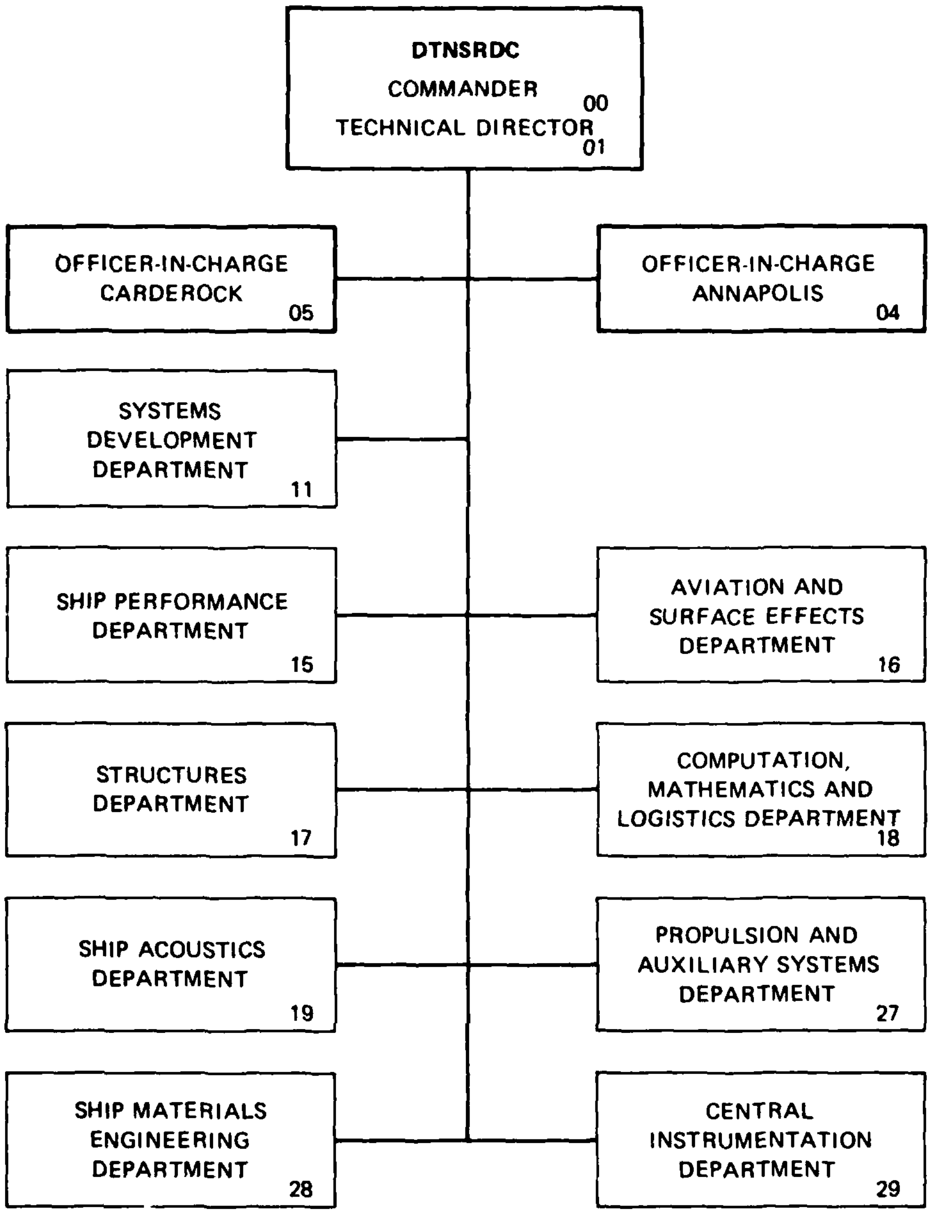
SHIP MATERIALS ENGINEERING DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

February 1981

DTNSRDC/SME-80/70

INFRARED TEMPERATURE SENSING OF COOLING RATES FOR ARC WELDING CONTROL

MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 14 DTNSRDC/SME-80/70	2. GOVT ACCESSION NO. AD-A096 049	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 INFRARED TEMPERATURE SENSING OF COOLING RATES FOR ARC WELDING CONTROL.		5. TYPE OF REPORT & PERIOD COVERED 9 Research and development rept.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 W. E. Lukens, R. A. Morris, ~~and~~ E. C. Dunn		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Bethesda, Maryland 20084 12 35		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 61152N 16 Project ZR00001 Work Unit 2822-130
11. CONTROLLING OFFICE NAME AND ADDRESS David W. Taylor Naval Ship R & D Center Bethesda, Maryland 20084		12. REPORT DATE 11 February 1981
		13. NUMBER OF PAGES 34
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Infrared
Cooling Rate
HY-130 Steel
Arc Welding
In-Process Control

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

It is known that the weld metal mechanical properties of quenched and tempered steels are dependent upon cooling rate, which is presently indirectly controlled by specification of heat input. A method to directly control weld metal cooling rate would result in more consistency in achieving required mechanical properties. In the present investigation the use of commercial infrared sensing equipment was explored as a means of real-time monitoring of weld metal cooling rate. Infrared equipment has a distinct advantage over other temperature detecting

(Continued on reverse side)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED 410660 alt

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Block 20 (Continued)

systems in that it requires no physical contact with the work, thus affording a minimum amount of interference with the welding process, and is therefore a potentially useful detector for an adaptive feedback welding control system based on cooling rate. It was found that infrared thermography appears to offer considerable promise for welding control by providing weld metal cooling rates which are: (1) reproducible, (2) sensitive to variations in welding conditions, and (3) relatable to cooling rates as measured by plunged thermocouples.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

A/D	Analog to digital
°C	Degree Celsius
cfh	Cubic feet per hour
DMA	Direct memory access
°F	Degree Fahrenheit
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HAZ	Heat affected zone
ID	Identification
IR	Infrared
°K	Degree Kelvin
kj	Kilojoule
ksi	Thousand pounds per square inch
l/min	Liter per minute
LOF	Lack of fusion
m	Meter
mm	Millimeter
NDE	Nondestructive evaluation
R_C	Rockwell C
μm	Micrometer

ABSTRACT

It is known that the weld metal mechanical properties of quenched and tempered steels are dependent upon cooling rate, which is presently indirectly controlled by specification of heat input. A method to directly control weld metal cooling rate would result in more consistency in achieving required mechanical properties. In the present investigation the use of commercial infrared sensing equipment was explored as a means of real-time monitoring of weld metal cooling rate. Infrared equipment has a distinct advantage over other temperature detecting systems in that it requires no physical contact with the work, thus affording a minimum amount of interference with the welding process, and is therefore a potentially useful detector for an adaptive feedback welding control system based on cooling rate. It was found that infrared thermography appears to offer considerable promise for welding control by providing weld metal cooling rates which are: (1) reproducible, (2) sensitive to variations in welding conditions, and (3) relatable to cooling rates as measured by plunged thermocouples.

ADMINISTRATIVE INFORMATION

This report was prepared under Work Unit 2822-130, Program Element 61152N, project ZR00001, titled, "Feedback Control of Arc Welding," as part of the Center Independent Research Program, managed by the Technical Director, Dr. A. Powell. The work reported herein was conducted under the supervision of Mr. F. J. Lengenfelder, Head, Titanium and Nonferrous Metals Fabrication Branch, and Mr. A. Pollack, Head, Ferrous Metals Fabrication Branch.

ACKNOWLEDGMENT

The authors wish to acknowledge Dr. I. Kramer, Code 2802, of this Center for technical guidance in support of this project.

INTRODUCTION

BACKGROUND

The Navy has placed great emphasis on developing welding procedures for quenched and tempered steels for naval applications. It is known that the weld metal microstructure and mechanical properties of quenched and tempered steels are dependent upon the rate at which the weld metal cools from the molten state to ambient temperature. The ability to directly control weld metal cooling rate during welding is difficult because of the many variables which affect it, such as: the energy input (amperage, voltage, and travel speed, which are

often referred to as the "welding parameters"); initial plate temperature; weld geometry (including thickness of the workpiece, shape and size of the weld deposit and angle between the pieces being joined); the electrode size; welding process; power supply polarity; and type of shielding gas. Cooling rate is generally indirectly controlled by specifying welding parameters which produce a certain calculated heat input and assuming this heat input corresponds to the desired weld metal cooling rate. A method to directly control weld metal cooling rate would improve the Navy's capability to consistently produce weldments having desired weld metal microstructure and mechanical properties. There has been no effort prior to this work to achieve desired cooling rates using an automatic adaptive control technique for in-process monitoring and real-time control of weld metal cooling rate.

In the present investigation the use of commercial infrared sensing equipment was explored as a means of real-time monitoring of weld metal cooling rate. Infrared equipment has a distinct advantage over other temperature detecting systems in that it requires no physical contact with the work, thus affording a minimum amount of interference with the welding process.

If infrared signals can be obtained with reasonable freedom from arc or electrode interference, they offer a heretofore neglected method of control for weld metal cooling rate. This would be performed by in-process control of welding current, arc voltage, and/or travel speed.

INFRARED THEORY

All objects having a temperature above absolute zero radiate energy. In the temperature range of interest in this study, the energy is referred to as "infrared radiation" and is electromagnetic in nature of wavelength between visible light and microwaves (0.75 – 1000 micrometers).[1]* Generally speaking, there are three types of radiation source, distinguished by the ways in which the spectral emittance (radiant power) of each varies with wavelength:

1. A blackbody, with an emissivity equal to unity. A blackbody absorbs all radiation that impinges upon it at any wavelength. Emissivity is defined as the ratio of the spectral radiant power from any object to that from a blackbody at the same temperature and wavelength.
2. A graybody, with an emissivity equal to a constant less than one.
3. A selective radiator, for which emissivity varies with wavelength.

The spectral energy distribution for blackbodies as determined by Planck's formula is shown in Figure 1.[2] Planck's formula, when plotted graphically for various temperatures, produces a family of curves. Following any of the Planck curves, the spectral emittance is zero at $\lambda = 0$, then increases rapidly to a maximum at wavelength λ maximum and approaches zero at very long wavelengths. The higher the temperature, the

*A complete listing of references is given on page 27.

shorter the wavelength at which the maximum occurs. The Stefan-Boltzmann formula, obtained by integrating Planck's formula from $\lambda = 0$ to $\lambda = \infty$, gives the total radiant emittance of a blackbody.

Most metals, including steel, are defined as graybodies having emissivities less than one.[3] The emissivity is generally dependent on the material and surface conditions. If the emissivity of a surface and the temperature of its surroundings are known, the radiance can be measured and the temperature of the body determined using the Stefan-Boltzmann law. This is the basis for the radiometric method of measuring temperature.

SCANNING RADIOMETER

The AGA Thermovision System 680 used in this study consists of an infrared camera and a thermal picture display.[4] The camera unit converts the invisible, infrared radiation given off by an object into equivalent electronic video signals which are then amplified and transferred via an interconnecting cable to the display unit. The IR-sensitive detector consists of an indium antimonide (InSb) photovoltaic cell, sensitive in the spectral range of 2 to 5.6 μm.* The signals from the camera unit are further amplified at the display unit and used to modulate the intensity of the electron beam of the TV-monitor tube in synchronism with the camera scanning optics, under control of trigger pulses arriving from the camera unit. This produces on the display screen a thermal picture of the object being scanned by the camera unit. Figure 2a shows a thermal picture of the workpiece and the welding torch. The horizontal accent line is adjusted to coincide with the deposited weld metal for weld metal cooling rate analysis.

THERMAL PROFILER

The thermal picture may be represented by a relief picture, Figure 2b, in which the height of each scan line is directly related to temperature.[4] Any one of the scan lines may be chosen for individual display, as shown in Figure 2c, by adjustment of the horizontal accent line. The temperature readings are not absolute and must therefore be correlated with temperatures as determined by thermocouple. Cooling rate data reported herein were obtained from calibrated selected profiles as shown in Figure 3. The abscissa in distance units was converted to time units through the equation

$$x = vt$$

*Definitions of abbreviations used are given on page v.

where x = distance

v = constant welding torch speed

t = time.

The slope at 538°C (1000°F) was then calculated, and the time to cool from 800°C (1472°F) to 400°C (752°F) was calculated as an alternate measure of cooling rate.

EXPERIMENTAL PROCEDURES

Two series of experiments were conducted. In the first series of tests gas tungsten arc bead-on-plate welds were produced and weld metal cooling rate was evaluated using the infrared equipment. The infrared cooling rate data was then compared to the welding parameters and to calculated weld heat input values.

In the second series of experiments gas metal arc bead-on-plate welds were produced using constant welding parameters in conjunction with various plate thicknesses to produce different weld metal cooling rates. For each bead the cooling rate was evaluated with the infrared equipment and by plunging a thermocouple into the molten weld metal at approximately the mid-length of the weld bead. The results of the two methods of weld metal cooling rate detection were then evaluated and compared.

In all the experiments the detection of weld metal cooling rate by infrared thermography was performed as described previously in the section titled Thermal Profiler. The plunged thermocouple cooling rates were determined using the procedures described by Dorschu[5] and Krantz and Coppolecchia.[6]

WELDING PROCEDURES

All the weld beads were produced bead-on-plate in the flat position under carefully controlled and monitored conditions.

The GTAW bead-on-plate tests were made using an automatic welding head equipped with arc voltage control. Electrodes were 5/32-in. (3.97-mm)-diameter thoriated tungsten, and welding was done with direct current, straight polarity. Shielding gas was argon at 60 cfh (2.83 l/min).

For GMAW bead-on-plate welding, the electrode was 0.062-in. (1.59-mm)-diameter MIL-140S-1 filler wire, and welding was done with direct current, reverse polarity. Shielding gas was argon 2% oxygen at 50 cfh (2.36 l/min).

For both GTAW and GMAW tests, the infrared scanner was positioned in a fixed location with respect to the workpiece, as shown in Figure 4.

TEST MATERIAL

For the GTAW weld tests, the plate material was 7/8- x 6- x 12-in. (22.2- x 152.4- x 304.8-mm) HY-130 steel. The GMAW weld tests were performed on HY-130 steel in thicknesses of 1/4, 3/8, 1/2, 3/4, and 7/8 in. The surfaces were ground prior to welding. The yield strength of HY-130 steel weld metal is sensitive to weld metal cooling rate, as shown in Figure 5, and is therefore an ideal candidate for this study.

RESULTS AND DISCUSSION

GAS TUNGSTEN ARC BEAD-ON-PLATE WELDS

The welding parameters of travel speed, welding current, and arc voltage were varied independently. All welding conditions were held constant during each experiment. Data taken from infrared scan lines in which travel speed, welding current, and arc voltage were systematically varied from experiment to experiment are shown in Figures 6 and 7. These data show that the cooling rate at 538°C (1000°F) as measured by the infrared scanner did vary measurably with the welding parameters, a basic requirement for the use of infrared detectors in a feedback control loop. The data from these figures is replotted in Figure 8 with heat input as the abscissa, where

$$\frac{\text{heat input}}{\text{unit length of weld}} = \frac{(\text{amperage})\ (\text{voltage})}{\text{travel speed}}$$

Another measure of cooling rate through the solid-state transformation range is time to cool from 800°C (1472°F) to 400°C (752°F). This parameter is plotted in Figure 9 as a function of heat input and also appears to be a parameter which could be used as a basis for control.

INTERFERENCE FROM TUNGSTEN ELECTRODE

A possible source of error in temperature measurements of the weld metal using infrared detection arises from radiation interference from the welding arc. Intense radiation of the ultraviolet, visible, and infrared wavelengths is emitted by all exposed welding arcs. The level of interference from the arc was kept at a minimum by use of the InSb detector which is sensitive to wavelengths between 2 and 5.6 μm. Most of the arc radiation occurs between 0.43 and 1.8 μm, which is below the 2-μm cutoff of the detector.[7]

A series of tests were performed wherein the gas tungsten arc was extinguished to permit examination of changes in the infrared signal. These tests confirmed that the arc radiation has an effect on the infrared signal

only in the vicinity of the arc and not at positions behind the arc where weld metal cooling rates are being measured.

GAS METAL ARC BEAD-ON-PLATE WELDS

A test program on GMAW bead-on-plate was undertaken in which the welding parameters were maintained constant and plate thickness was varied as a means of varying cooling rate. The cooling rate as measured by infrared scanner was reproducible and compared favorably with the cooling rate as measured by thermocouple plunges. The tabulated data, Table 1, is plotted in Figure 10. The infrared scanner measures only surface temperatures, while the thermocouples are plunged to an average depth of approximately 2 mm (0.08 in.) as shown in Figure 11. The difference in cooling rate between a point at the surface and a point 2 mm (0.08 in.) beneath the surface could be responsible for the difference between cooling rate as determined by infrared and thermocouple methods. However, the most important aspect of this series of experiments was the demonstration of reproducibility of the infrared measurements.

TABLE 1 — WELD METAL COOLING RATES AT 1000°F (538°C)
(INFRARED VS THERMOCOUPLE)

Thickness in.	Series ID	Cooling Rate, °F/sec (°C/sec) at 1000°F (538°C)	
		Thermocouple	IR
1/4	A1	9.8 (5.4)	11 (6.1)
	A2	9.5 (5.3)	*
	A3	8.5 (4.7)	11 (6.1)
	F1	9.6 (5.3)	9 (6.0)
	F2	9.2 (5.1)	11 (6.1)
	F3	9.6 (5.3)	12 (6.7)
		Avg 9.4 (5.2)	11 (6.1)
3/8	B1	16.5 (9.2)	18 (10.0)
	B2	17.8 (9.9)	18 (10.0)
	B3	18.2 (10.1)	19 (10.6)
		Avg 17.5 (9.7)	18 (10.0)
1/2	C1	25.9 (14.4)	33 (18.3)
	C2	34.2 (19.0)	42 (23.3)
	C3	32.9 (18.3)	45 (25.0)
		Avg 31.0 (17.2)	40 (22.2)
3/4	D1	47.5 (26.4)	66 (36.7)
	D2	53.5 (29.7)	66 (36.7)
	D3	53.5 (29.7)	66 (36.7)
		Avg 51.5 (28.6)	66 (36.7)
7/8	E1	71.3 (39.6)	90 (50.0)
	E2	65.8 (36.6)	102 56.7)
	E3	**	72 (40.0)
	E4	61.1 (33.9)	90 (50.0)
		Avg 66.1 (36.7)	89 (49.4)

*Film not readable.
**Thermocouple melted.

In addition samples were prepared from the GMAW bead-on-plate welds for metallographic examination and hardness testing. These samples were polished and etched and are presented in Figures 12, 13, and 14.

TABLE 2 — ROCKWELL C HARDNESS

Weld ID	Thermocouple Cooling Rate °F/sec (°C/sec) at 1000°F (538°C)	IR Cooling Rate °F/sec (°C/sec) at 1000°F (538°C)	Average R_C Hardness*		
			Weld	HAZ	Base
F	9.5 (5.3)	11 (6.1)	31	36	30
B	17.5 (9.7)	18 (10.0)	35	36	32
C	31.0 (17.1)	40 (22.2)	35	34	30
D	51.5 (28.6)	66 (36.7)	38	40	30
E	66.0 (36.7)	89 (49.4)	38	39	31

*Average of three tests.

The hardness values are presented in Table 2. The welds show a progression from a *martensitic* microstructure at the rapid cooling rates to a bainitic microstructure at the slower cooling rates. The microstructure identification is based on visual examination, hardness readings, and comparison with previous work on HY-130 steel weld metal microstructure versus weld metal cooling rate reported by Morris.*

EMISSIVITY EFFECTS

Since the infrared radiation from a material is a function of both temperature and emissivity, variations in surface emissivity have a large impact on apparent temperature. The emissivity of steel can vary greatly depending on surface condition from 0.07 for a polished surface to 0.79 for an oxidized surface.[8]

It was found that the GTAW and GMAW welds were characterized by uniformly oxidized surfaces which exhibited uniform emissivity, a condition which greatly alleviates the potential problems which could arise from emissivity variation of the measured surface. Under some welding conditions, it was possible to observe the abrupt change in emissivity between the unoxidized weld metal under the torch gas and the oxidized weld metal after it lost its torch shielding, as shown in Figure 2c, where an abrupt change in the otherwise smoothly varying curve is apparent. The capability to detect changes in surface condition through emissivity provides a basis for NDE of titanium welds as discussed in the Recommendations section.

*As described by Morris in a report with restricted distribution.

SUMMARY AND CONCLUSIONS

1. Infrared thermography appears to offer considerable promise for GTAW and GMAW control by providing weld metal cooling rates which are: (a) reproducible; (b) sensitive to variations in arc voltage, amperage and travel speed, and plate thickness; and (c) relatable to cooling rates as measured by plunged thermocouples.

2. Infrared radiation from the GTAW and GMAW arcs does not interfere with weld metal cooling rate determinations.

3. The effect of emissivity on the accuracy of the weld metal temperature measurements is minimized by the fact that the oxide coating on the HY-130 steel weld metal is rather uniform and therefore exhibits a uniform emissivity.

RECOMMENDATIONS

The results and conclusions presented in this report encourage further investigation into the following fields of study, all of which combine infrared thermography as the method of detecting characteristics of the weldment or of the parameters involved in welding.

1. The Thermal History of the Welded Workpiece. To date in this program, investigations were limited to weld metal cooling rate at 538°C (1000°F) and time to cool from 800°C (1472°F) to 400°C (752°F). Thermal gradients at higher temperatures (up to the melting point) should be investigated to gain insight into their effect on solidification structure. The effect of plate heating in front of the arc ("bow wave effect") should also be investigated as a method for preheating. Finally, fluctuation in amperage, voltage, preheat, geometry and thickness, and shielding gas flow, which occur commonly during welding, should be systematically investigated to determine the response of cooling rate.

2. Detection of Lack-of-Fusion Defects. Lack-of-fusion defects provide an effective barrier to heat flow in metals and may therefore be detected through anomalies in the thermal patterns during welding. This area of study should be investigated as potentially valuable for on-line NDE.

3. NDE of Titanium Weld Surface Contamination. Emissivity changes of the weld metal surface can be detected by infrared thermography, as shown in Figure 2c, on HY-130 steel. The same principle applied to titanium would provide the basis for a quantitative on-line method to detect weld surface contamination.

4. In-Process Control. A data base established in the above fields of study should be analyzed to establish a relationship between the particular characteristic of the weld and the detected infrared signal. In the case of thermal history of the workpiece, the required temperature profile ranges should be established so that they may be automatically maintained through a feedback control system. Figure 15 shows schematically how the thermal monitoring system can be implemented into a practical welding system. In the cases of LOF

defects and weld surface contamination, on-line detection would permit immediate shutdown of the welding process until the defects were removed and the conditions then corrected.

FUTURE WORK

Up to this point in the program, thermal data analysis was restricted to the single scan line along the weld joint which includes the recently deposited weld metal. A more complete and rapid thermal analysis would require digitization because: (1) the total thermal pattern of the plate, during welding, is complex and cannot be easily quantified by analog methods; (2) the heat pattern changes (sometimes rapidly) as a function of variations in parameters which affect cooling rate; and (3) rapid analysis can only be performed by digitized automatic data processing. Digital data analysis is useful for interpretation of the many thermograms generated during a single welding experiment and for comparison between experiments. A more consistent and accurate result is attainable through digitization. To achieve this goal, a PDP 11/34 minicomputer was obtained for direct interfacing with the Thermovision 680. The hardware consists of the Thermovision connected directly to the PDP 11/34 via an A/D converter and a DMA channel. Each thermal picture is represented by a digitized 128 X 128 matrix.[9] Figure 16 shows an on-line system where the Thermovision analog output is analyzed in real time. Digital data analysis accomplished through direct interface of the Thermovision to a minicomputer can provide a sophisticated method to rapidly analyze the effect of welding parameters on the temperature distribution in the workpiece during welding, in addition to providing a basis for adaptive feedback control. Future data analysis under this program will make use of this capability.

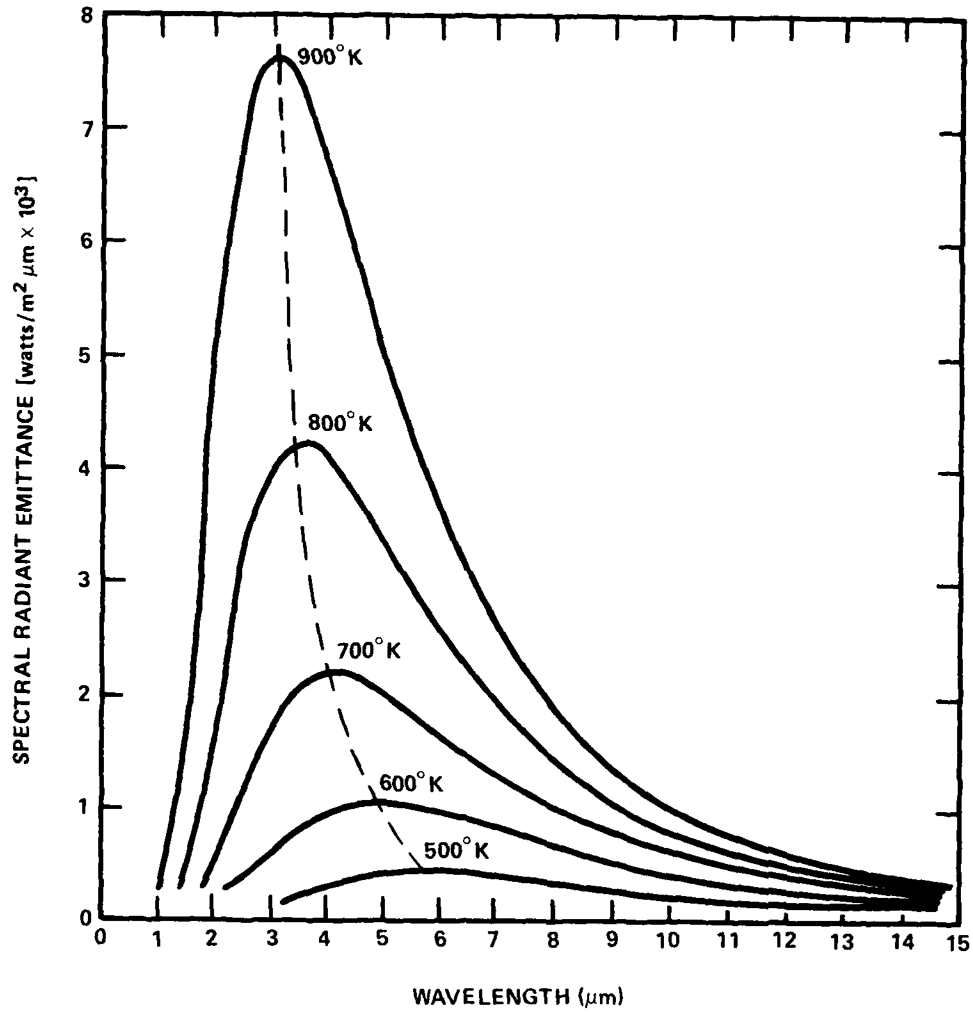


Figure 1 - Blackbody Spectral Radiant Emittance
According to Planck's Law,
Plotted for Various Temperatures (Reference 2)

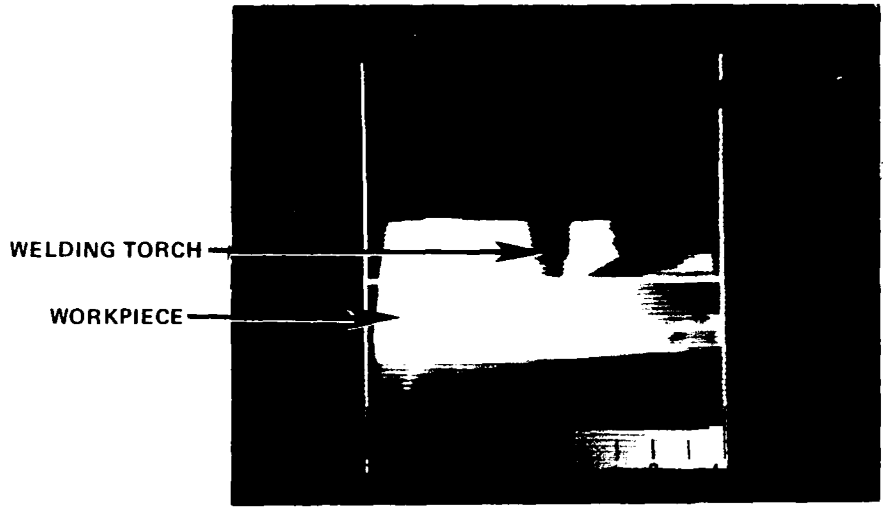


Figure 2a - Gray Scale

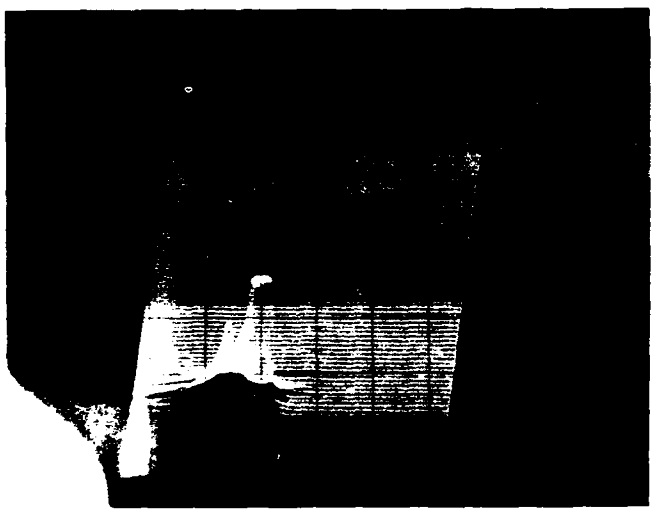


Figure 2b - Relief

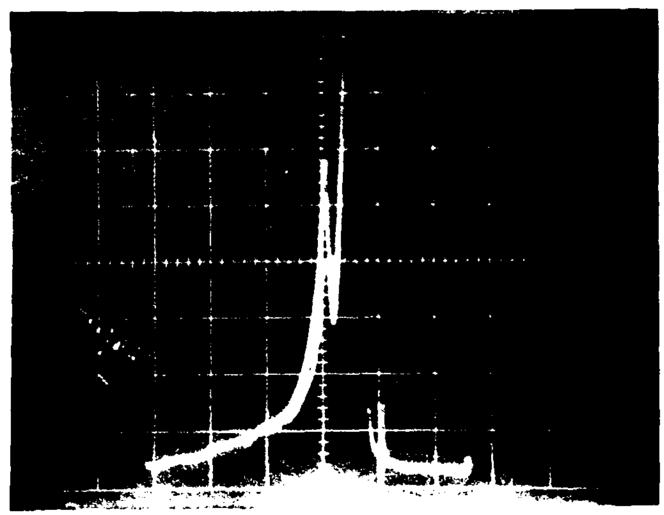


Figure 2c - Selected Profile

Figure 2 - Infrared Representation of Temperature

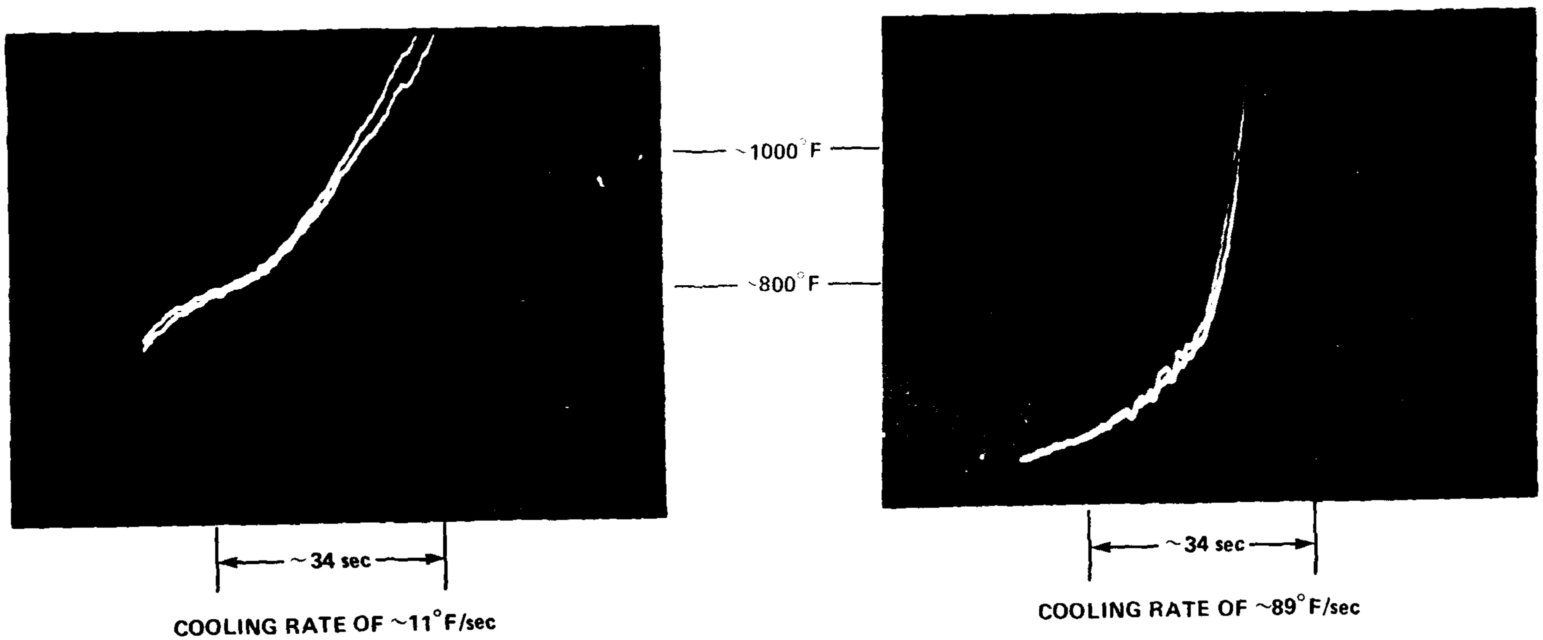


Figure 3 - Infrared Cooling Curves

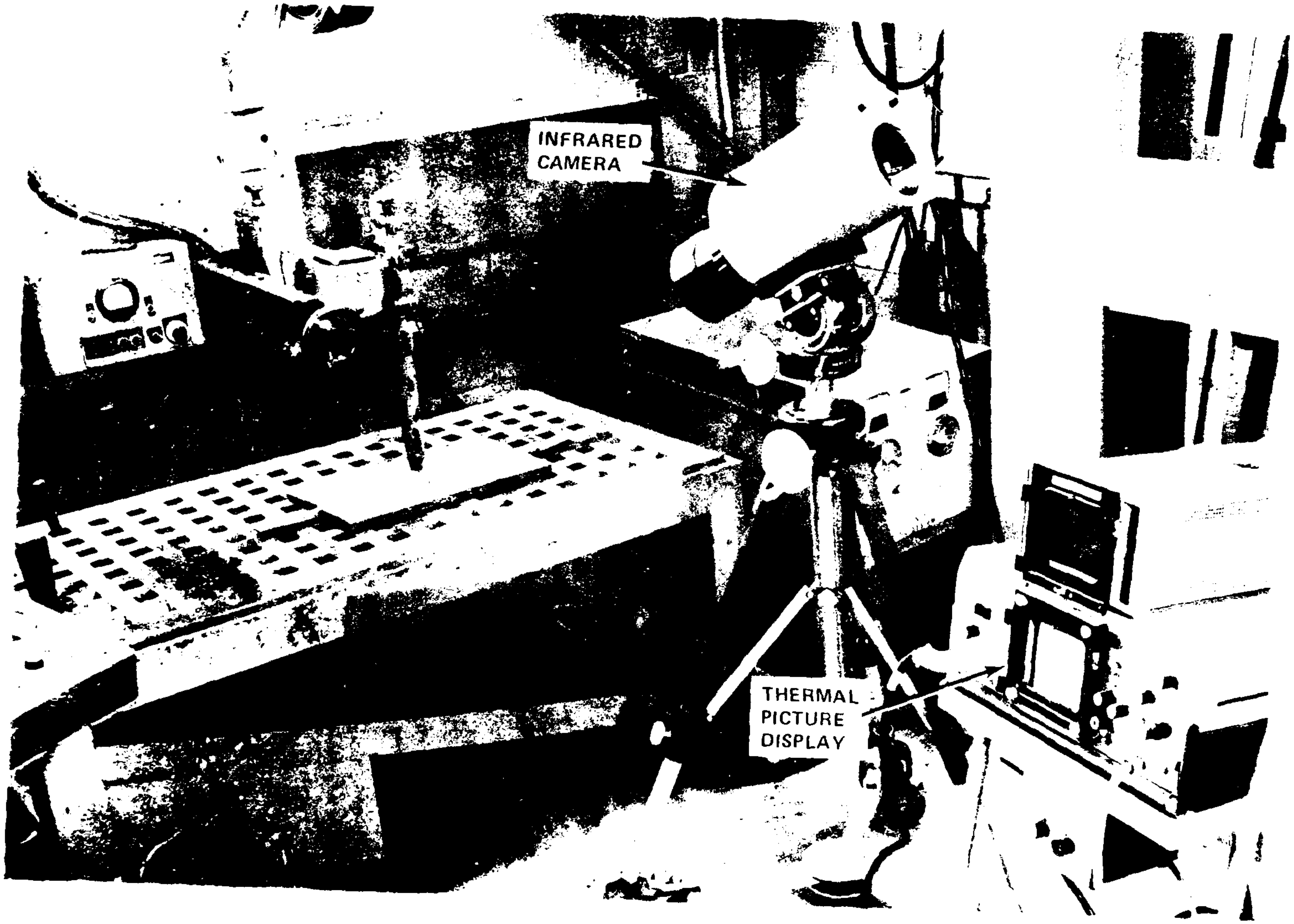


Figure 4 - Infrared Weld Monitoring Equipment

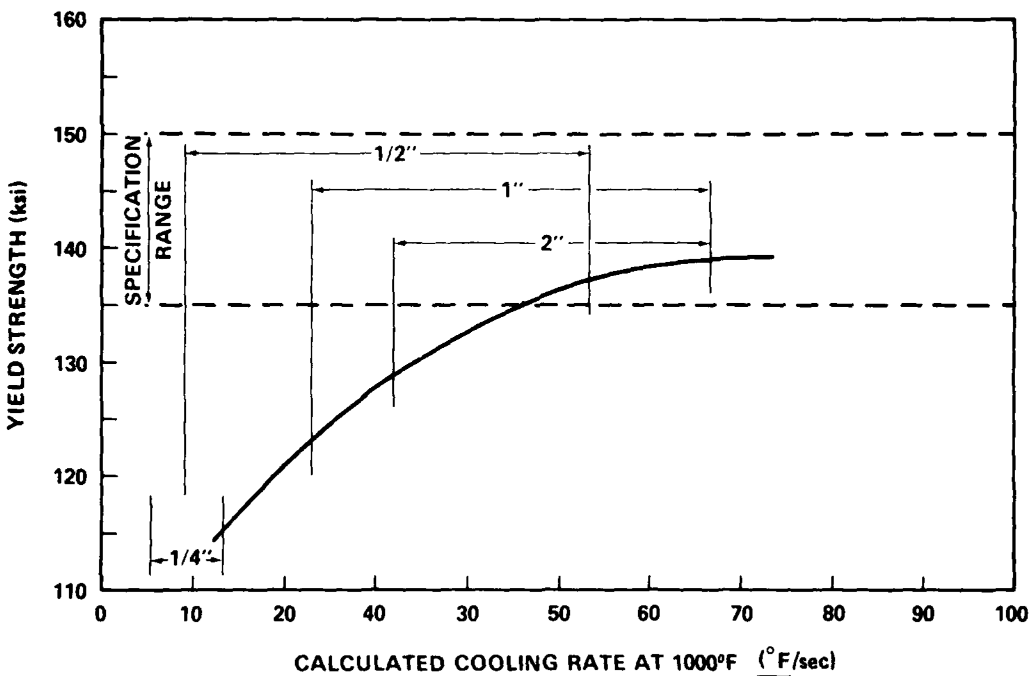


Figure 5 - Yield Strength Versus Weld Cooling Rate (0.045-Inch-Diameter, MIL-140S Electrodes, Vertical Pulsed GMAW)

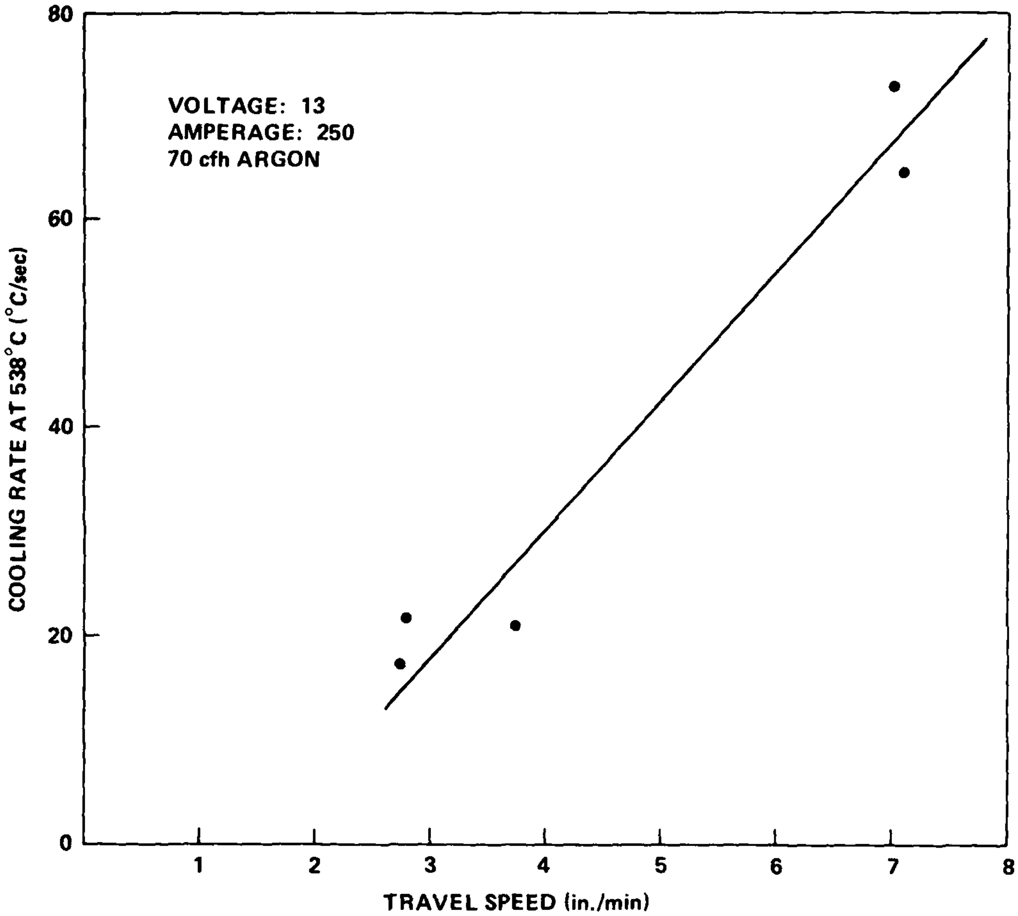


Figure 6 - Effect of Weld Travel Speed on Cooling Rate

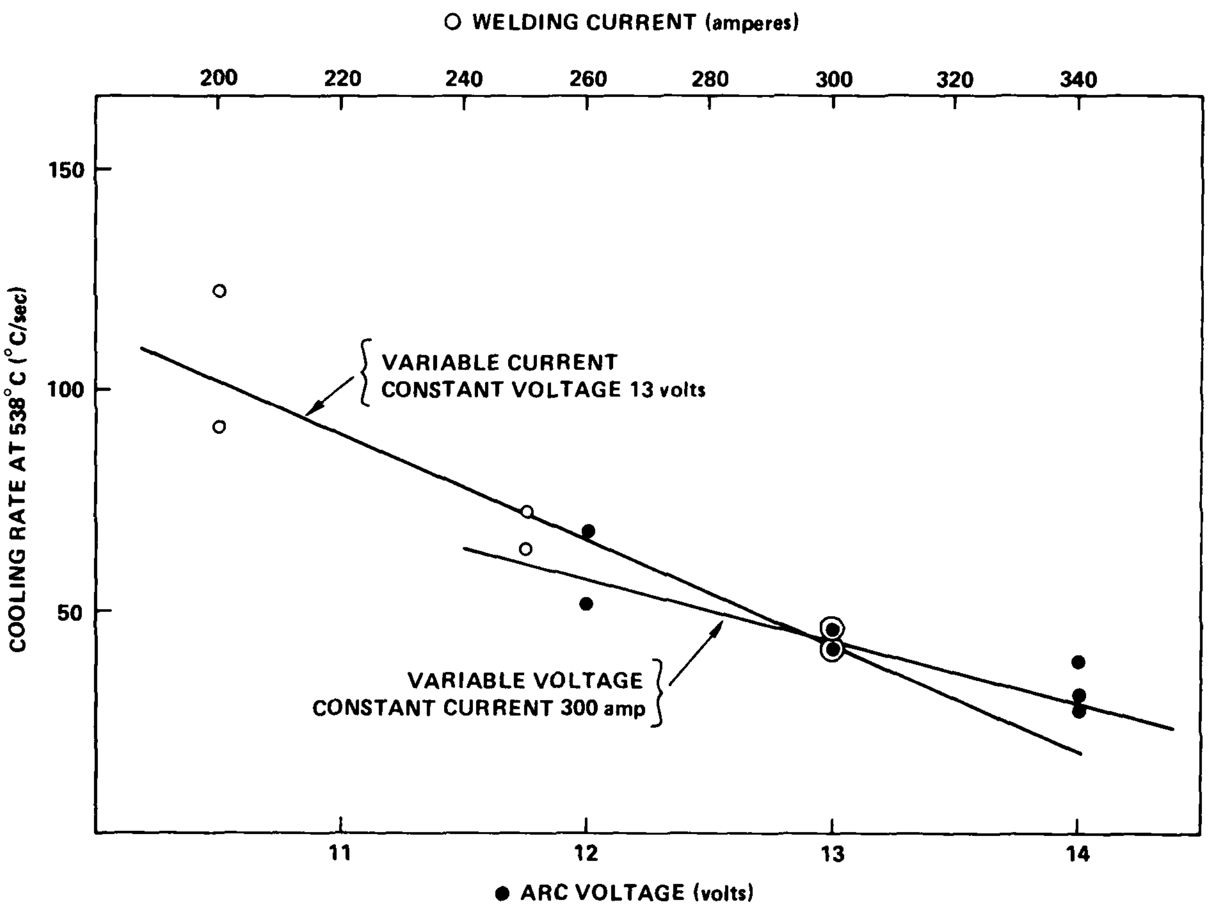


Figure 7 - Effect of Weld Voltage and Amperage on Cooling Rate

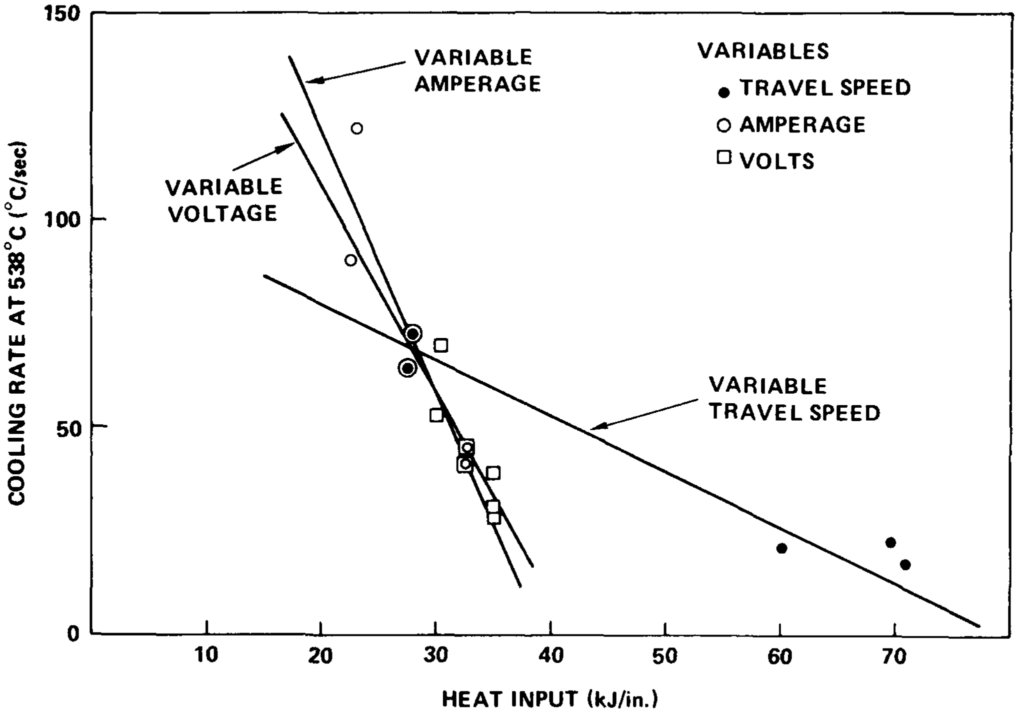


Figure 8 - Effect of Heat Input on Cooling Rate

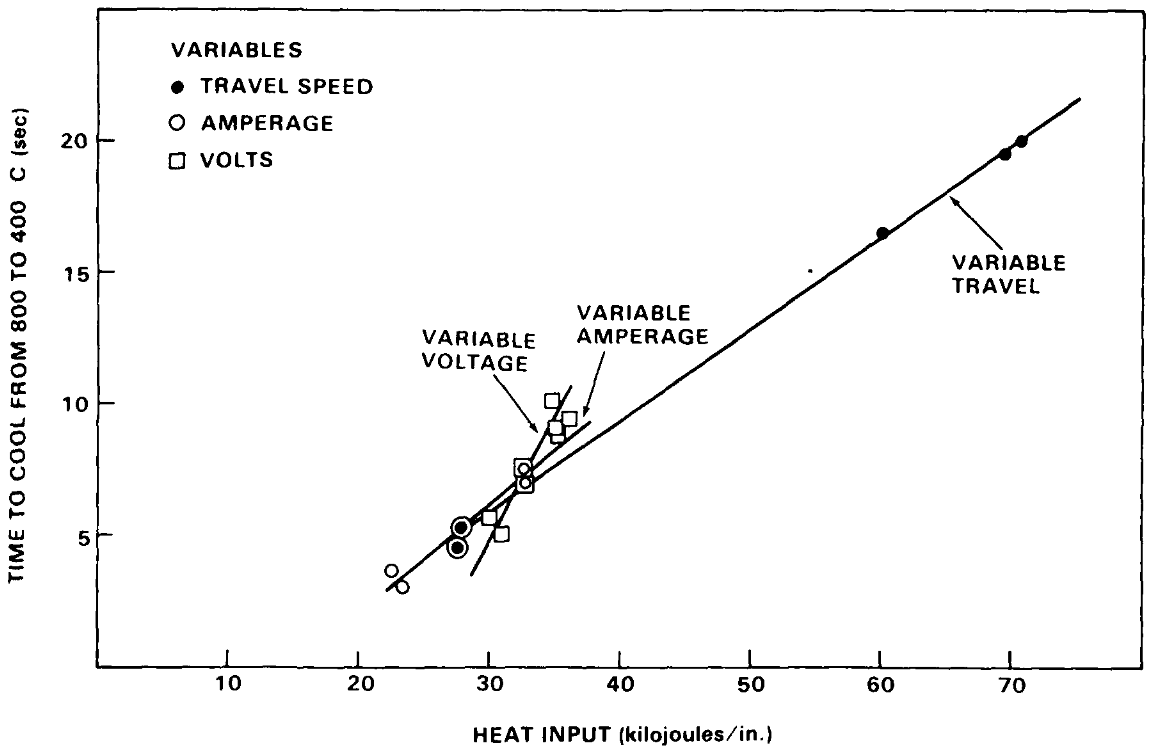


Figure 9 - Effect of Heat Input on Time to Cool

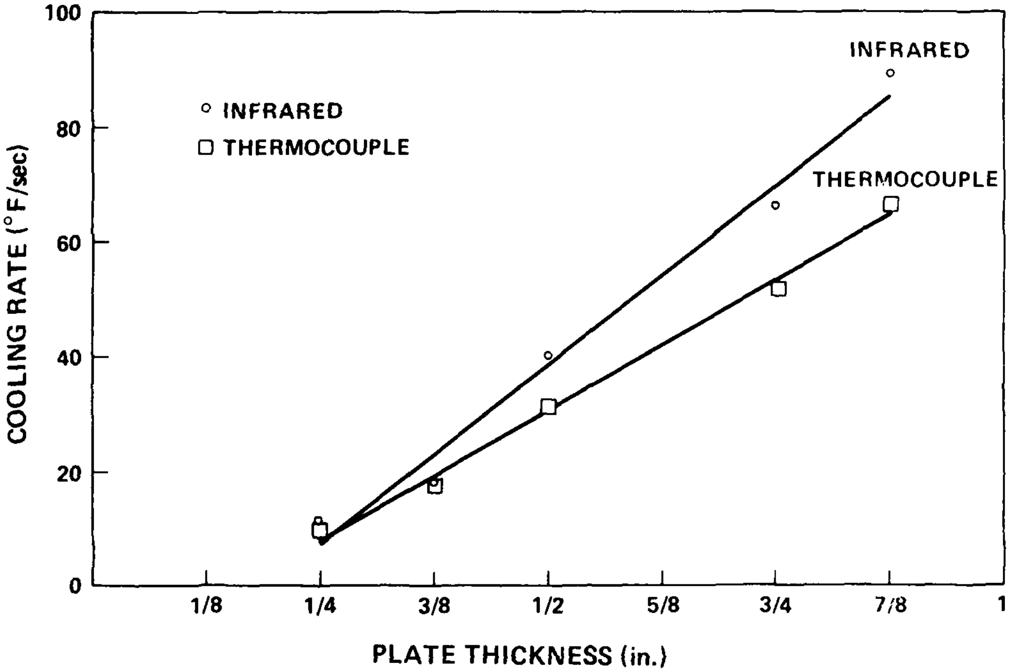


Figure 10 - Cooling Rate Determinations, Infrared Versus Thermocouple

Figure 11 - Cross Section of Typical Plunged Thermocouple (6X)

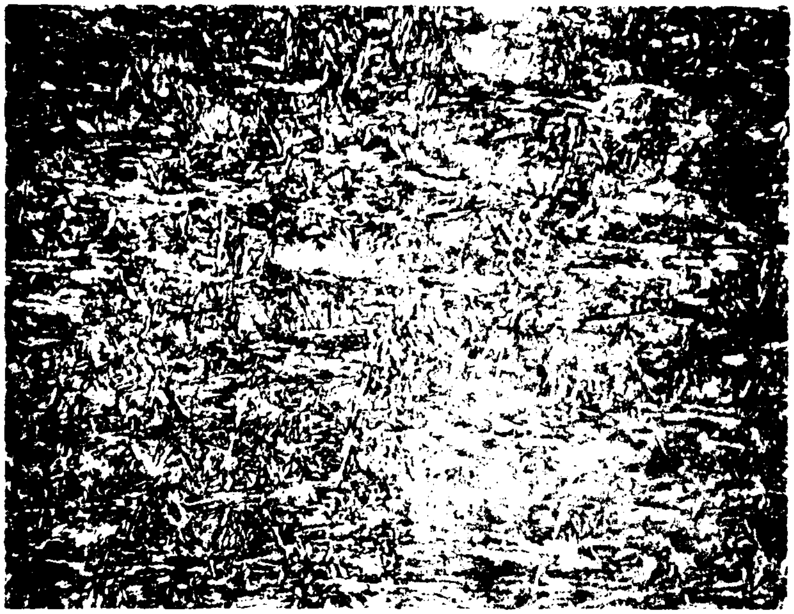


Figure 12a - Thermocouple Cooling Rate - 9.4°F/sec
Infrared Cooling Rate - 11°F/sec

Figure 12b - Thermocouple Cooling Rate - 17.5°F/sec
Infrared Cooling Rate - 18°F/sec

Figure 12 - Microstructures of Gas Metal Arc Bead-on-Plate Welds (500X)

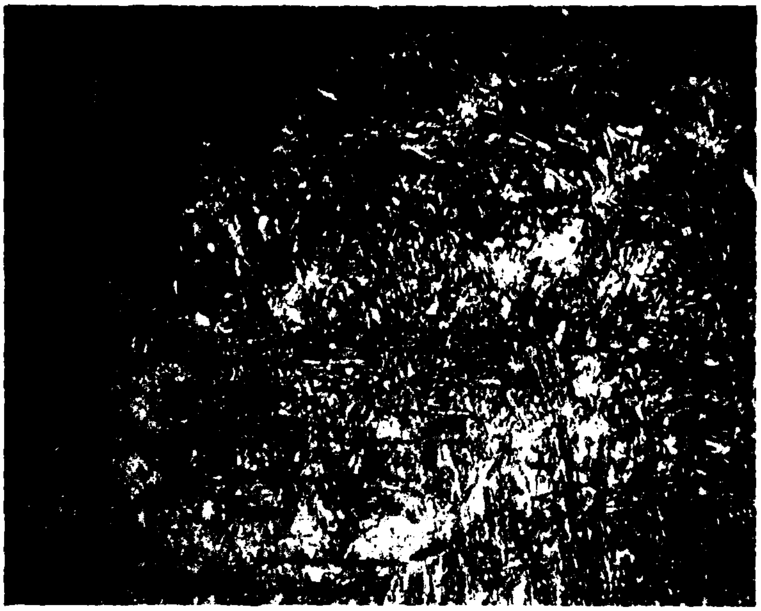


Figure 13a - Thermocouple Cooling Rate - 31.0^{O}F/sec
Infrared Cooling Rate - 40^{O}F/sec

Figure 13b - Thermocouple Cooling Rate - 51.5^{O}F/sec
Infrared Cooling Rate - 66^{O}F/sec

Figure 13 - Microstructures of Gas Metal Arc
Bead-on-Plate Welds (500X)

Thermocouple Cooling Rate - 66.1°F/sec
Infrared Cooling Rate - 89°F/sec

Figure 14 - Microstructure of Gas Metal Arc Bead-on-Plate Weld (500X)

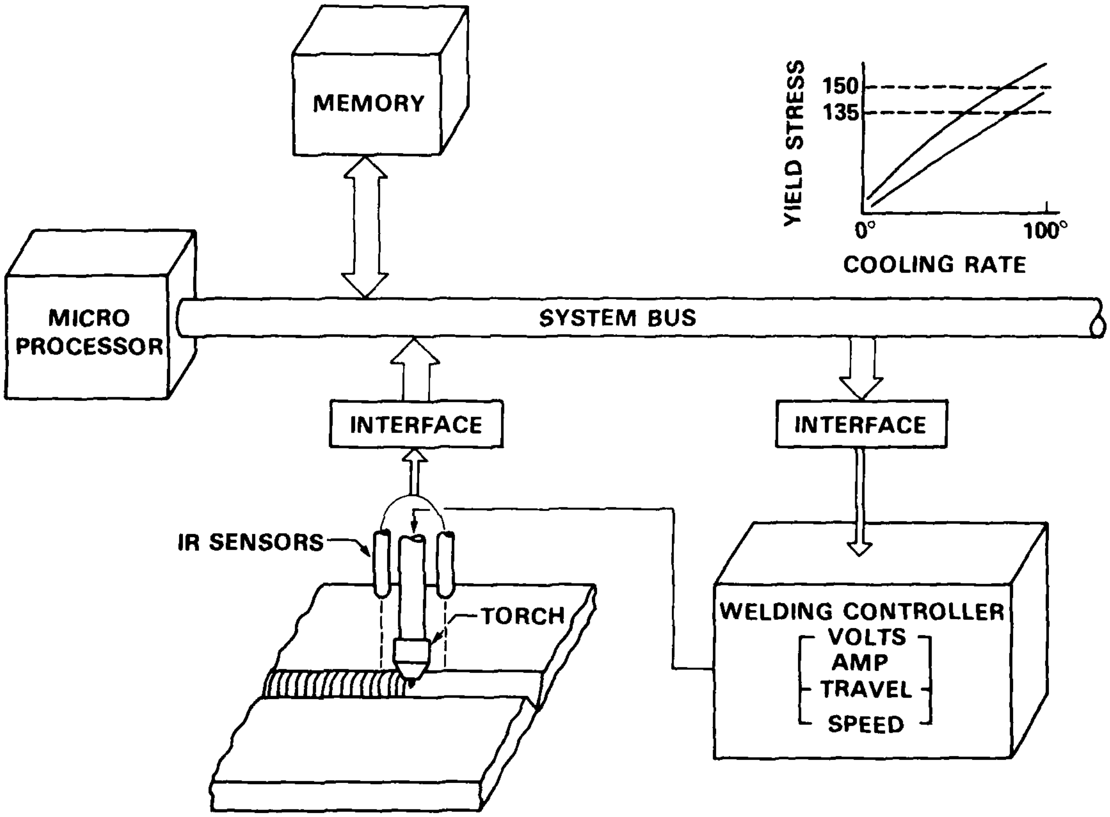


Figure 15 - In-Process Welding Control System

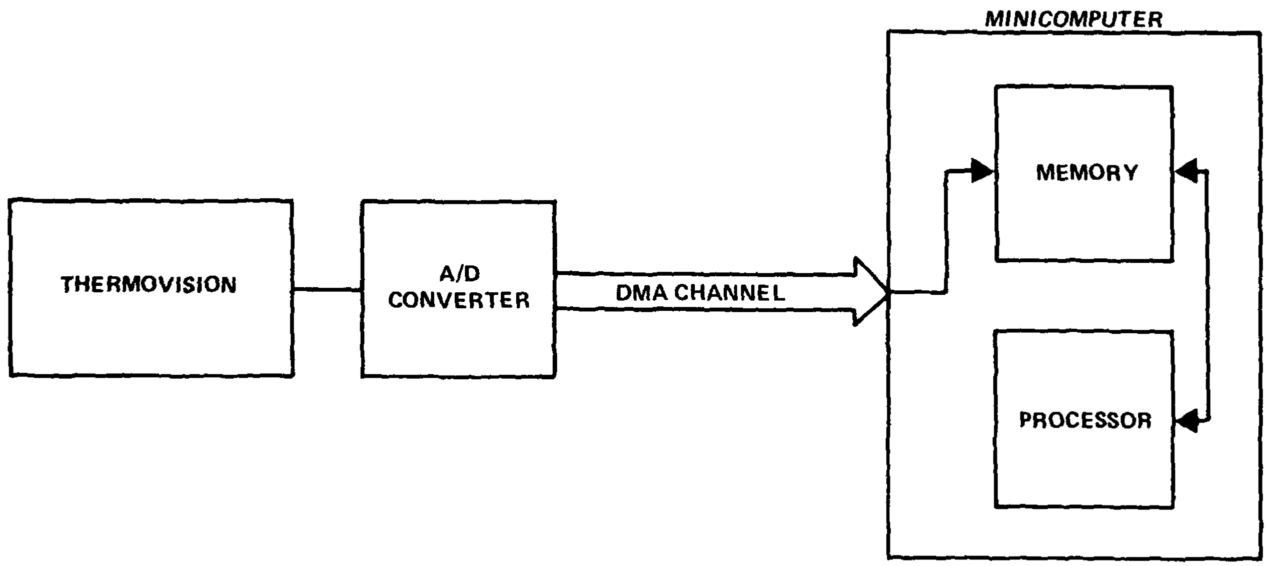


Figure 16 - Real-Time Digitization System

REFERENCES

1. "The Infrared Handbook," Edited by William L. Wolfe and George J. Zissis, Office of Naval Research, Department of the Navy, Washington, DC (1978), "Detectors" (Thomas Limperis and Joseph Mudar), pp. 1-103.

2. "The Infrared Handbook," Edited by William L. Wolfe and George J. Zissis, Office of Naval Research, Department of the Navy, Washington, DC (1978), "Radiation Theory" (William L. Wolfe), pp. 1-15.

3. Ramsay, P. W. et al., "Infrared Temperature Sensing Systems for Automatic Fusion Welding," Welding Journal, Vol. 42, No. 8, pp. 337s-346s (1963).

4. "AGA Thermovision® 680 Operating Manual," AGA Infrared Systems AB, Lidingo, Sweden (1975), "Section 3-Operating Principles," pp. 3-1 to 3-6.

5. Dorschu, K. E., "Control of Cooling Rate in Steel Weld Metal," Welding Journal, Vol. 47, No. 2, pp. 49s-62s (1968).

6. Krantz, Boris M. and Vincent D. Coppolecchia, "The Effects of Pulsed Gas Metal Arc Welding Parameters on Weld Cooling Rates," Welding Journal, Vol. 50, No. 11, pp. 474s-479s (1971).

7. "Welding Handbook," Seventh Edition, Vol. 1, American Welding Society (1976), "Arc Characteristics," pp. 54-55.

8. "The Infrared Handbook," Edited by William L. Wolfe and George J. Zissis, Office of Naval Research, Department of the Navy, Washington, DC (1978), "Artificial Sources" (Anthony J. LaRocca), pp. 1-97.

9. "AGA Infrared Systems Computer Interfacing Guidebook," Copyright © 1977 by AGA Corporation, "Various Computer Approaches" (Cliff Warren and Ake Frojdh), pp. 19-25.

INITIAL DISTRIBUTION

Copies	
6	Director of Navy Laboratories
1	NRL Code 6000
1	ONR Code 471
1	ONR/Chicago
1	NAVMAT MAT 034
6	NAVSEA
	1 SEA 05D
	1 SEA 05R15
	2 SEA 99612
	1 SEA 321
	1 SEA 323
12	DTIC

CENTER DISTRIBUTION

Copies	Code
1	01
1	012
1	17
1	2802
1	2803
1	2809H
2	282
10	2821
10	2822
1	522.1
2	5231

DTNSRDC ISSUES THREE TYPES OF REPORTS

1. DTNSRDC REPORTS, A FORMAL SERIES, CONTAIN INFORMATION OF PERMANENT TECHNICAL VALUE. THEY CARRY A CONSECUTIVE NUMERICAL IDENTIFICATION REGARDLESS OF THEIR CLASSIFICATION OR THE ORIGINATING DEPARTMENT.

2. DEPARTMENTAL REPORTS, A SEMIFORMAL SERIES, CONTAIN INFORMATION OF A PRELIMINARY, TEMPORARY, OR PROPRIETARY NATURE OR OF LIMITED INTEREST OR SIGNIFICANCE. THEY CARRY A DEPARTMENTAL ALPHANUMERICAL IDENTIFICATION.

3. TECHNICAL MEMORANDA, AN INFORMAL SERIES, CONTAIN TECHNICAL DOCUMENTATION OF LIMITED USE AND INTEREST. THEY ARE PRIMARILY WORKING PAPERS INTENDED FOR INTERNAL USE. THEY CARRY AN IDENTIFYING NUMBER WHICH INDICATES THEIR TYPE AND THE NUMERICAL CODE OF THE ORIGINATING DEPARTMENT. ANY DISTRIBUTION OUTSIDE DTNSRDC MUST BE APPROVED BY THE HEAD OF THE ORIGINATING DEPARTMENT ON A CASE-BY-CASE BASIS.